

Implications of the R_K and R_{K^*} anomalies

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We discuss the implications of the recently reported R_K and R_{K^*} anomalies, the lepton flavor non-universality in the $B \rightarrow K\ell^+\ell^-$ and $B \rightarrow K^*\ell^+\ell^-$. Using two sets of hadronic inputs of form factors, we perform a fit of the new physics to the R_K and R_{K^*} data, and significant new physics contributions are found. We propose to study the lepton flavor universality in a number of related rare B, B_s, B_c and Λ_b decay channels, and in particular we point out the μ -to- e ratios of decay widths with different polarizations of the final state particles, and of the $b \rightarrow d\ell^+\ell^-$ processes are presumably more sensitive to the structure of the underlying new physics. With the new physics contributions embedded in Wilson coefficients, we present theoretical predictions for lepton flavor non-universality in these processes.

I. INTRODUCTION

The standard model (SM) of particle physics is now completed by the discovery of Higgs boson. Thus the focus in particle physics has been gradually switched to the search for new physics (NP) beyond the SM. This can proceed in two distinct ways. One is the direct search at the high energy frontier, in which new particles beyond the SM are produced and detected directly. The other is called indirect search, which is at the high intensity frontier. The new particles will presumably manifest themselves as intermediate loop effects, and might be detectable by low-energy experiments with high precision.

In flavor physics, the $b \rightarrow s\ell^+\ell^-$ process is a flavor changing neutral current (FCNC) transition. This process is of special interest since it is induced by loop effects in the SM, which leads to tiny branching fractions. Many extensions of the SM can generate sizable effects that can be experimentally validated. In particular, the $B \rightarrow K^*(\rightarrow K\pi)\mu^+\mu^-$ decay offers a large number of observables to test the SM, ranging from the differential decay widths, polarizations, to a full analysis of angular distributions of the final state particles, for an incomplete list one can refer to Refs. [1–19] and many references therein.

In the past few years, quite a few observables in the channels mediated by $b \rightarrow s\ell^+\ell^-$ transition have exhibited deviations from the SM expectations. The LHCb experiment has first observed the so-called P'_5 anomaly, a sizeable discrepancy at 3.7σ between the measurement and the SM prediction in one bin for the angular observable P'_5 [20]. This discrepancy was reproduced in a later LHCb analysis for the two adjacent bins at large K^* recoil [21]. To accommodate this discrepancy,

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considerable attentions have been paid to explore new physics contributions (see Refs. [22–28] and references therein), while at the same time, this has also triggered the thoughts to revisit the hadronic uncertainties [29, 30].

More strikingly, the LHCb measurement of the ratio [31]:

$$R_K[q_{\min}^2, q_{\max}^2] \equiv \frac{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 d\Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)/dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 d\Gamma(B^+ \rightarrow K^+ e^+ e^-)/dq^2}, \quad (1)$$

gives a hint for the lepton flavour universality violation (LFUV). A plausible speculation is that deviations from the SM are present in $b \rightarrow s\mu^+\mu^-$ transitions instead in $b \rightarrow se^+e^-$ ones. Very recently the LHCb collaboration has found sizable differences between $B \rightarrow K^*e^+e^-$ and $B \rightarrow K^*\mu^+\mu^-$ at both low q^2 region and central q^2 region [32]. Results for ratios

$$R_{K^*}[q_{\min}^2, q_{\max}^2] \equiv \frac{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 d\Gamma(B \rightarrow K^* \mu^+ \mu^-)/dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 d\Gamma(B \rightarrow K^* e^+ e^-)/dq^2}, \quad (2)$$

are given in Tab. I, from which we can see the data showed significant deviations from unity. These interesting results have subsequently attracted many theoretical attentions [33–47].

TABLE I: Ratios of decay widths with a pair of muons and electrons in $B \rightarrow K\ell^+\ell^-$ and $B \rightarrow K^*\ell^+\ell^-$.

Observables	SM results	Experimental data
$R_K : q^2 = [1, 6] \text{ GeV}^2$	1.00 ± 0.01 [48]	$0.745_{-0.074}^{+0.090} \pm 0.036$ [31]
$R_{K^*}^{\text{low}} : q^2 = [0.045, 1.1] \text{ GeV}^2$	$0.920_{-0.006}^{+0.007}$ [36]	$0.660_{-0.070}^{+0.110} \pm 0.024$ [32]
$R_{K^*}^{\text{central}} : q^2 = [1.1, 6] \text{ GeV}^2$	0.996 ± 0.002 [36]	$0.685_{-0.069}^{+0.113} \pm 0.047$ [32]

The statistics significance in the data is low at this stage, about 3σ level. In order to obtain more conclusive results, one should measure the muon-versus-electron ratios in the $B \rightarrow K\ell^+\ell^-$ and $B \rightarrow K^*\ell^+\ell^-$ more precisely, meanwhile one should also investigate more channels with better sensitivities to the structures of new physics contributions. In this paper, we will focus on the latter. To do so, we will first discuss the implications of the R_K and R_{K^*} anomalies in a model-independent way, where the new particle contributions are parameterized in terms of effective operators. Since there is lack of enough data, we analyze their impact on the Wilson coefficients of SM operators $O_{9,10}$. We then propose to study the lepton flavor universality in a number of rare B, B_s, B_c and Λ_b decay channels. Incorporating the new physics contributions, we will present the predictions for the muon-versus-electron ratios in these channels, making use of various updates of form factors [49–54]. We will demonstrate that the measurements of lepton flavor non-universality with different polarizations of the final state hadron, and in the $b \rightarrow d\ell^+\ell^-$ processes are of great value to decode the structure of the underlying new physics.

The rest of this paper is organized as follows. In the next section, we will use a model-independent approach and quantify the new physics effects in terms of the short-distance Wilson

coefficients. In Section III, we will study the LFUV in various FCNC channels. Our conclusion is given in the last section.

II. IMPLICATIONS FROM THE R_K AND R_{K^*}

In this section, we will first study the impact of the R_K and R_{K^*} data. In the SM, the effective Hamiltonian for the transition $b \rightarrow s\ell^+\ell^-$

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^* \sum_{i=1}^{10} C_i(\mu)O_i(\mu)$$

involves the four-quark and the magnetic penguin operators O_i . Here $C_i(\mu)$ are the Wilson coefficients for these local operators O_i . G_F is the Fermi constant, V_{tb} and V_{ts} are CKM matrix elements. The dominant contributions to $b \rightarrow s\ell^+\ell^-$ come from the following operators:

$$\begin{aligned} O_7 &= \frac{em_b}{8\pi^2}\bar{s}\sigma^{\mu\nu}(1+\gamma_5)bF_{\mu\nu} + \frac{em_s}{8\pi^2}\bar{s}\sigma^{\mu\nu}(1-\gamma_5)bF_{\mu\nu}, \\ O_9 &= \frac{\alpha_{\text{em}}}{2\pi}(\bar{l}\gamma_\mu l)\bar{s}\gamma^\mu(1-\gamma_5)b, \quad O_{10} = \frac{\alpha_{\text{em}}}{2\pi}(\bar{l}\gamma_\mu\gamma_5 l)\bar{s}\gamma^\mu(1-\gamma_5)b. \end{aligned} \quad (3)$$

The above effective Hamiltonian gives the $B \rightarrow K\ell^+\ell^-$ decay width as:

$$\begin{aligned} \frac{d\Gamma(B \rightarrow K\ell^+\ell^-)}{dq^2} &= \frac{G_F^2\sqrt{\lambda}\alpha_{\text{em}}^2\beta_l}{1536m_B^3\pi^5}|V_{tb}V_{ts}^*|^2 \times \left[\lambda(1+2\hat{m}_l^2) \left| C_9f_+(q^2) + C_7\frac{2m_b f_T(q^2)}{m_B+m_K} \right|^2 \right. \\ &\quad \left. + \lambda\beta_l^2|C_{10}|^2 f_+^2(q^2) + 6\hat{m}_l^2|C_{10}|^2(m_B^2-m_K^2)^2 f_0^2(q^2) \right], \end{aligned} \quad (4)$$

where $\hat{m}_l = m_l/\sqrt{q^2}$, $\beta_l = \sqrt{1-\hat{m}_l^2}$, $\lambda = (m_B^2 - m_K^2 - q^2)^2 - 4m_K^2 q^2$, and f_+ , f_0 and f_T are the $B \rightarrow K$ form factors. In the above expression, we have neglected the non-factorizable contributions which are expected to be negligible for R_K .

The decay width for $B \rightarrow K^*\ell^+\ell^-$ can be derived in terms of the helicity amplitude [55–59]. The differential decay width is given as

$$\frac{d\Gamma(B \rightarrow K^*\ell^+\ell^-)}{dq^2} = \frac{3}{4}(I_1^c + 2I_1^s) - \frac{1}{4}(I_2^c + 2I_2^s), \quad (5)$$

with

$$\begin{aligned} I_1^c &= (|A_{L0}^1|^2 + |A_{R0}^1|^2) + 8\hat{m}_l^2\text{Re}[A_{L0}^1 A_{R0}^{1*}] + 4\hat{m}_l^2|A_t^1|^2, \\ I_1^s &= (3/4 - \hat{m}_l^2)[|A_{L\perp}^1|^2 + |A_{L\parallel}^1|^2 + |A_{R\perp}^1|^2 + |A_{R\parallel}^1|^2] + 4\hat{m}_l^2\text{Re}[A_{L\perp}^1 A_{R\perp}^{1*} + A_{L\parallel}^1 A_{R\parallel}^{1*}], \\ I_2^c &= -\beta_l^2(|A_{L0}^1|^2 + |A_{R0}^1|^2), \\ I_2^s &= \frac{1}{4}\beta_l^2(|A_{L\perp}^1|^2 + |A_{L\parallel}^1|^2 + |A_{R\perp}^1|^2 + |A_{R\parallel}^1|^2). \end{aligned} \quad (6)$$

The handedness label L or R corresponds to the chirality of the di-lepton system. Functions $A_{L/Ri}$

can be expressed in terms of $B \rightarrow K^*$ form factors

$$A_t^1 = 2\sqrt{N_{K_j^*}}N_1C_{10}\frac{\sqrt{\lambda}}{\sqrt{q^2}}A_0(q^2), \quad (7)$$

$$A_{L0}^1 = \frac{N_1\sqrt{N_{K_j^*}}}{2m_{K_j^*}\sqrt{q^2}} \left[(C_9 - C_{10})[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})A_1 - \frac{\lambda}{m_B + m_{K^*}}A_2] \right. \\ \left. + 2m_bC_7[(m_B^2 + 3m_{K^*}^2 - q^2)T_2 - \frac{\lambda}{m_B^2 - m_{K^*}^2}T_3] \right], \quad (8)$$

$$A_{L\perp}^1 = -\sqrt{2N_{K_j^*}}N_1 \left[(C_9 - C_{10})\frac{\sqrt{\lambda}V}{m_B + m_{K^*}} + \frac{2m_bC_7}{q^2}\sqrt{\lambda}T_1 \right], \quad (9)$$

$$A_{L||}^1 = \sqrt{2N_{K_j^*}}N_1 \left[(C_9 - C_{10})(m_B + m_{K^*})A_1 + \frac{2m_bC_7}{q^2}(m_B^2 - m_{K^*}^2)T_2 \right], \quad (10)$$

with $N_1 = \frac{iG_F}{4\sqrt{2}}\frac{\alpha_{em}}{\pi}V_{tb}V_{ts}^*$, $N_{K_j^*} = 8/3\sqrt{\lambda}q^2\beta_l/(256\pi^3m_B^3)$ and $\lambda \equiv (m_B^2 - m_{K^*}^2 - q^2)^2 - 4m_{K^*}^2q^2$. The right-handed decay amplitudes are obtained by reversing the sign of C_{10} :

$$A_{Ri} = A_{Li}|_{C_{10} \rightarrow -C_{10}}. \quad (11)$$

Within the SM, one can easily find that results for R_K and R_{K^*} are extremely close to 1 and thus deviate from the experimental data. If new physics is indeed present, it can be in $b \rightarrow s\mu^+\mu^-$ and/or $b \rightarrow se^+e^-$ transitions. In order to explain the R_K and R_{K^*} data, one can enhance the partial width for the electronic mode or reduce the one for the muonic mode. It seems that the SM result for the $B \rightarrow Ke^+e^-$ is consistent with the data, and thus here we will adopt the strategy that the muonic decay width is reduced by new physics.

After integrating out the high scale intermediate states the new physics contributions can be incorporated into the effective operators. As there is lack of enough data that shows significant deviations with SM, we will assume that NP contributions can be incorporated into Wilson coefficients C_9 and C_{10} . For this purpose, we define

$$\delta C_9^\mu = C_9^\mu - C_9^{\text{SM}}, \quad \delta C_{10}^\mu = C_{10}^\mu - C_{10}^{\text{SM}}. \quad (12)$$

The O_7 contribution to $b \rightarrow s\ell^+\ell^-$ arises from the coupling of a photon with the lepton pair. On one hand, this coupling is highly constrained from the $b \rightarrow s\gamma$ data. On the other hand, this coefficient is flavor blinded and thus even if NP affect C_7 , the μ -to- e will not be affected.

For the analysis, we adopt three scenarios,

1. Only C_9 is affected with $\delta C_9^\mu \neq 0$.
2. Only C_{10} is affected with $\delta C_{10}^\mu \neq 0$.
3. Both C_9 and C_{10} are affected in the form: $\delta C_9^\mu = -\delta C_{10}^\mu \neq 0$.

Using the R_K and R_{K^*} data, we show our results in FIG. 1. The left panel corresponds to scenario 1, and the middle panel corresponds to the constraint on δC_{10}^μ , the last one corresponds to the

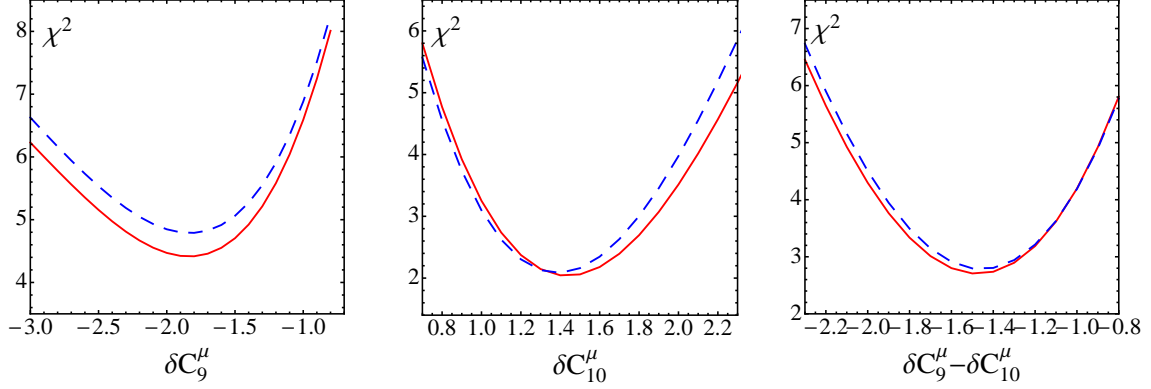


FIG. 1: Impact of R_K and R_{K^*} data on the δC_9^μ (left panel), δC_{10}^μ (central panel) or $\delta C_9^\mu - \delta C_{10}^\mu$ (right panel). The solid (red) and dashed (blue) curve corresponds to the form factors from LQCD [53, 62] and LCSR [60, 61], respectively.

scenario 3 with a nonzero $\delta C_9^\mu - \delta C_{10}^\mu$. In this analysis, we have used two sets of $B \rightarrow K$ and $B \rightarrow K^*$ form factors. One is from the light-cone sum rules (LCSR) [60, 61], corresponding to the dashed curves. The other is from Lattice QCD (LQCD) [53, 62], which gives the solid curves. As one can see clearly from the figure, the results are not sensitive to the form factors, and this also partly validate the neglect of other hadronic uncertainties like non-factorizable contributions. Using the LQCD set of form factors [53, 62], we found the best-fitted central value and the 1σ range for δC_9^μ in scenario 1 as

$$\delta C_9^\mu = -1.83, \quad -2.63 < \delta C_9^\mu < -1.25. \quad (13)$$

For scenario 2, we have

$$\delta C_{10}^\mu = 1.43, \quad 1.04 < \delta C_{10}^\mu < 1.89, \quad (14)$$

while for the $\delta C_9^\mu = -\delta C_{10}^\mu$, we obtain

$$\delta C_9^\mu - \delta C_{10}^\mu = -1.47, \quad -1.89 < \delta C_9^\mu - \delta C_{10}^\mu < -1.08. \quad (15)$$

All these scenarios can describe the R_K and R_{K^*} data well.

Explicit models which can realize these scenarios include the flavor non-universal Z' model, leptoquark model and vector-like models, see, e.g., Refs. [63–85] and many references therein. Their generic contributions are shown in FIG. 2. Taking the Z' model as an example, the SM can be extended by including an additional $U(1)'$ symmetry, which can leads to the Lagrangian of $Z'\bar{b}s$ couplings

$$\mathcal{L}_{\text{FCNC}}^{Z'} = -g'(B_{sb}^L \bar{s}_L \gamma_\mu b_L + B_{sb}^R \bar{s}_R \gamma_\mu b_R) Z'^\mu + \text{h.c.} \quad (16)$$

It contributes to the $b \rightarrow s \ell^+ \ell^-$ decay at tree level

$$\mathcal{H}_{\text{eff}}^{Z'} = \frac{8G_F}{\sqrt{2}} (\rho_{sb}^L \bar{s}_L \gamma_\mu b_L + \rho_{sb}^R \bar{s}_R \gamma_\mu b_R) (\rho_{ll}^L \bar{\ell}_L \gamma^\mu \ell_L + \rho_{ll}^R \bar{\ell}_R \gamma^\mu \ell_R), \quad (17)$$

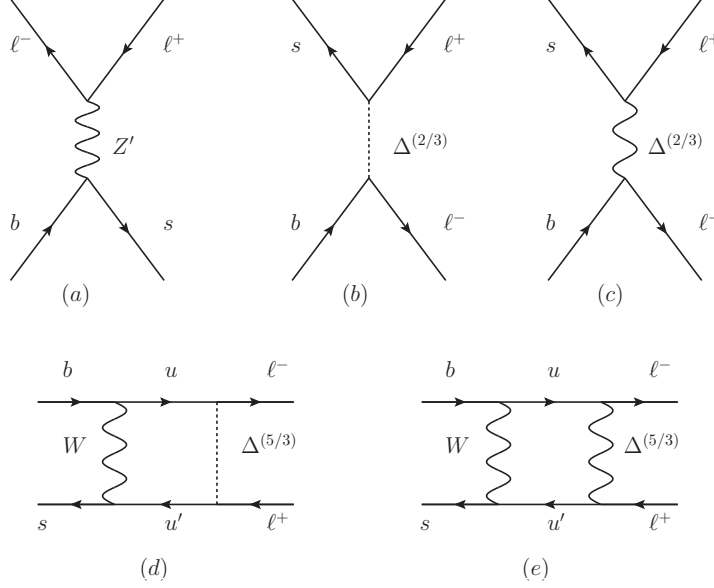


FIG. 2: New physics scenarios that can contribute to $b \rightarrow s\mu^+\mu^-$. The panel (a) shows a Z' , and in the other four diagrams Δ denotes a leptoquark with different spins and charges.

where the coupling is

$$\rho_{ff'}^{L,R} \equiv \frac{g' M_Z}{g M_{Z'}} B_{ff'}^{L,R} \quad (18)$$

where the g standard model $SU(2)_L$ coupling. For simplicity, one can assume that the FCNC couplings of the Z' and quarks only occur in the left-handed sector: $\rho_{sb}^R = 0$. Thus in this case the effects of the Z' will modify the Wilson coefficients C_9 and C_{10} :

$$C_9^{Z'} = C_9 - \frac{4\pi}{\alpha_{\text{em}}} \frac{\rho_{sb}^L (\rho_{ll}^L + \rho_{ll}^R)}{V_{tb} V_{ts}^*}, \quad C_{10}^{Z'} = C_{10} + \frac{4\pi}{\alpha_{\text{em}}} \frac{\rho_{sb}^L (\rho_{ll}^L - \rho_{ll}^R)}{V_{tb} V_{ts}^*}. \quad (19)$$

This corresponds to the scenario 1 and 2 in our previous analysis.

III. LEPTON FLAVOR UNIVERSALITY IN FCNC CHANNELS

In this section, we will study the μ -to- e ratios of decay widths in various FCNC channels. Since the three scenarios considered in the last section describe the data equally well, we will choose the first one for illustration in the following. We follow a similar definition

$$R_{B,M}[q_{\min}^2, q_{\max}^2] \equiv \frac{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 d\Gamma(B \rightarrow M\mu^+\mu^-)/dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 d\Gamma(B \rightarrow Me^+e^-)/dq^2}, \quad (20)$$

where B denotes a heavy particle and M denotes a final state. The channels to be studied include $B \rightarrow K_{0,2}^*(1430)\ell^+\ell^-$, $B_s \rightarrow f_0(980)\ell^+\ell^-$, $B \rightarrow K_1(1270)\ell^+\ell^-$, $B_s \rightarrow f_2(1525)\ell^+\ell^-$, $B_s \rightarrow \phi\ell^+\ell^-$,

$B_c \rightarrow D_s \ell^+ \ell^-$, $B_c \rightarrow D_s^* \ell^+ \ell^-$. The expressions for their decay widths have been given in the last section. In addition, we will also analyze on the R ratio for the baryonic decay $\Lambda_b \rightarrow \Lambda \ell^+ \ell^-$. The differential decay width for $\Lambda_b \rightarrow \Lambda \ell^+ \ell^-$ is given as [86]

$$\frac{d\Gamma}{dq^2}(\Lambda_b \rightarrow \Lambda \ell^+ \ell^-) = 2K_{1ss} + K_{1cc}, \quad (21)$$

where

$$\begin{aligned} K_{1ss}(q^2) &= \frac{1}{4} \left[|A_{\perp 1}^R|^2 + |A_{\parallel 1}^R|^2 + 2|A_{\perp 0}^R|^2 + 2|A_{\parallel 0}^R|^2 + (R \leftrightarrow L) \right], \\ K_{1cc}(q^2) &= \frac{1}{2} \left[|A_{\perp 1}^R|^2 + |A_{\parallel 1}^R|^2 + (R \leftrightarrow L) \right]. \end{aligned} \quad (22)$$

The functions A are defined as

$$\begin{aligned} A_{\perp 1}^{L(R)} &= \sqrt{2}N \left[(C_9 \mp C_{10}) H_+^V - \frac{2m_b C_7}{q^2} H_+^T \right], \quad A_{\parallel 1}^{L(R)} = -\sqrt{2}N \left[(C_9 \mp C_{10}) H_+^A + \frac{2m_b C_7}{q^2} H_+^{T5} \right], \\ A_{\perp 0}^{L(R)} &= \sqrt{2}N \left[(C_9 \mp C_{10}) H_0^V - \frac{2m_b C_7}{q^2} H_0^T \right], \quad A_{\parallel 0}^{L(R)} = -\sqrt{2}N \left[(C_9 \mp C_{10}) H_0^A + \frac{2m_b C_7}{q^2} H_0^{T5} \right]. \end{aligned} \quad (23)$$

where the normalization factor N is

$$N = G_F V_{tb} V_{ts}^* \alpha_{\text{em}} \sqrt{\frac{q^2 \sqrt{\lambda(m_{\Lambda_b}^2, m_{\Lambda}^2, q^2)}}{3 \cdot 2^{11} m_{\Lambda_b}^3 \pi^5}}. \quad (24)$$

The helicity amplitudes are given by

$$\begin{aligned} H_0^V &= f_0^V(q^2) \frac{m_{\Lambda_b} + m_{\Lambda}}{\sqrt{q^2}} \sqrt{s_-}, \quad H_+^V = -f_{\perp}^V(q^2) \sqrt{2s_-}, \\ H_0^A &= f_0^A(q^2) \frac{m_{\Lambda_b} - m_{\Lambda}}{\sqrt{q^2}} \sqrt{s_+}, \quad H_+^A = -f_{\perp}^A(q^2) \sqrt{2s_+} \\ H_0^T &= -f_0^T(q^2) \sqrt{q^2} \sqrt{s_-}, \quad H_+^T = f_{\perp}^T(q^2) (m_{\Lambda_b} + m_{\Lambda}) \sqrt{2s_-}, \\ H_0^{T5} &= f_0^{T5}(q^2) \sqrt{q^2} \sqrt{s_+}, \quad H_+^{T5} = -f_{\perp}^{T5}(q^2) (m_{\Lambda_b} - m_{\Lambda}) \sqrt{2s_+}, \end{aligned} \quad (25)$$

where $s_{\pm} \equiv (m_{\Lambda_b} \pm m_{\Lambda})^2 - q^2$. The $f_{0/\perp}^i$ with $i = V, A, T, T5$ are the $\Lambda_b \rightarrow \Lambda$ form factors.

The $B_s \rightarrow \phi \ell^+ \ell^-$ and $\Lambda_b \rightarrow \Lambda$ form factors are used from LQCD calculation in Refs. [53, 87], respectively. The $B \rightarrow K_0^*(1430)$ and $B_s \rightarrow f_0(980)$ form factors are taken from Ref. [49, 88]. The $B \rightarrow K_1(1270)$ form factors are calculated in the perturbative QCD approach [51], and the mixing angle between $K_1(1^{++})$ and $K_1(1^{+-})$ is set to be approximately 45° . In this case the $B \rightarrow K_1(1400) \ell^+ \ell^-$ is greatly suppressed [89]. The $B \rightarrow K_2$ and $B_s \rightarrow f_2(1525)$ form factors are taken from Ref. [52]. The $B_c \rightarrow D_s/D_s^*$ form factors are provided in light-front quark model [50], and in this work we have calculated the previously-missing tensor form factors. Using the Wilson coefficient δC_9^μ in Eq. (13), we present our numerical results for $R_{B,M}$ in TABLE II. Three kinematics regions are chosen in the analysis: low q^2 with $[0.045, 1]$ GeV², central q^2 with

TABLE II: Theoretical results for the μ -to- e ratio $R_{B,M}$ of decay widths as defined in Eq. (20) in various $b \rightarrow s\ell^+\ell^-$ channels. Three kinematics regions are chosen: low, central and high q^2 regions. Wilson coefficient C_9 is used as in Eq. (13) based on the analysis of R_K and R_{K^*} . For a vector final state, the longitudinal and transverse polarizations are separated and labeled as L and T , respectively. For $\Lambda_b \rightarrow \Lambda\ell^+\ell^-$, a similar decomposition is used: the superscript 0 means that the Λ_b and Λ have the same polarization, while 1 corresponds to different polarizations.

Observable	Low $q^2 : [0.045, 1]\text{GeV}^2$	Central $q^2 : [1, 6]\text{GeV}^2$	High $q^2 : [14\text{GeV}^2, q_{\text{max}}^2]$
$R_{B,K_0^*}(1430)$	$0.688^{+0.075}_{-0.073}$	$0.702^{+0.076}_{-0.075}$	$0.721^{+0.074}_{-0.074}$
$R_{B_s,f_0}(980)$	$0.687^{+0.074}_{-0.074}$	$0.700^{+0.076}_{-0.076}$	$0.707^{+0.075}_{-0.074}$
R_{B_c,D_s}	$0.686^{+0.075}_{-0.075}$	$0.699^{+0.077}_{-0.077}$	$0.706^{+0.076}_{-0.076}$
$R_{B_s,\phi}$	$0.863^{+0.016}_{-0.010}$	$0.772^{+0.051}_{-0.040}$	$0.710^{+0.071}_{-0.067}$
$R_{B_s,\phi}^L$	$0.697^{+0.074}_{-0.074}$	$0.701^{+0.076}_{-0.076}$	$0.706^{+0.073}_{-0.071}$
$R_{B_s,\phi}^T$	$0.975^{+0.024}_{-0.034}$	$1.059^{+0.049}_{-0.108}$	$0.712^{+0.070}_{-0.065}$
R_{B_c,D_s^*}	$0.926^{+0.006}_{-0.012}$	$0.940^{+0.003}_{-0.034}$	$0.749^{+0.056}_{-0.041}$
$R_{B_c,D_s^*}^L$	$0.704^{+0.066}_{-0.059}$	$0.719^{+0.067}_{-0.060}$	$0.736^{+0.060}_{-0.049}$
$R_{B_c,D_s^*}^T$	$0.956^{+0.015}_{-0.021}$	$1.289^{+0.113}_{-0.182}$	$0.756^{+0.053}_{-0.037}$
R_{B,K_2^*}	$0.851^{+0.017}_{-0.011}$	$0.759^{+0.055}_{-0.044}$	$0.718^{+0.068}_{-0.062}$
$R_{B,K_2^*}^L$	$0.675^{+0.075}_{-0.076}$	$0.696^{+0.077}_{-0.077}$	$0.713^{+0.070}_{-0.065}$
$R_{B,K_2^*}^T$	$0.983^{+0.026}_{-0.038}$	$1.051^{+0.049}_{-0.109}$	$0.721^{+0.066}_{-0.059}$
R_{B_s,f_2}	$0.858^{+0.014}_{-0.008}$	$0.767^{+0.052}_{-0.040}$	$0.720^{+0.067}_{-0.060}$
R_{B_s,f_2}^L	$0.675^{+0.075}_{-0.075}$	$0.697^{+0.076}_{-0.076}$	$0.716^{+0.069}_{-0.063}$
R_{B_s,f_2}^T	$0.982^{+0.026}_{-0.037}$	$1.063^{+0.052}_{-0.114}$	$0.723^{+0.065}_{-0.058}$
$R_{B,K_1}(1270)$	$0.909^{+0.008}_{-0.004}$	$0.880^{+0.002}_{-0.002}$	$0.714^{+0.069}_{-0.065}$
$R_{B,K_1}^L(1270)$	$0.751^{+0.085}_{-0.094}$	$0.717^{+0.088}_{-0.100}$	$0.712^{+0.071}_{-0.067}$
$R_{B,K_1}^T(1270)$	$0.978^{+0.025}_{-0.036}$	$1.078^{+0.056}_{-0.118}$	$0.714^{+0.069}_{-0.064}$
$R_{\Lambda_b,\Lambda}$	$0.931^{+0.014}_{-0.007}$	$0.773^{+0.051}_{-0.039}$	$0.712^{+0.071}_{-0.068}$
$R_{\Lambda_b,\Lambda}^0$	$0.708^{+0.073}_{-0.070}$	$0.705^{+0.074}_{-0.072}$	$0.707^{+0.073}_{-0.072}$
$R_{\Lambda_b,\Lambda}^1$	$1.071^{+0.023}_{-0.032}$	$1.104^{+0.060}_{-0.124}$	$0.715^{+0.070}_{-0.065}$

$[1, 6] \text{ GeV}^2$ and high q^2 region with $[14 \text{ GeV}^2, q_{\text{max}}^2 = (m_B - m_M)^2]$. For a vector final state, the longitudinal and transverse polarizations are separated and labeled as L and T , respectively. For $\Lambda_b \rightarrow \Lambda\ell^+\ell^-$, a similar decomposition is used, in which the superscript 0 means the Λ_b and Λ have the same polarization while 1 corresponds to different polarizations.

A few remarks are given in order.

- From the decay widths for $B \rightarrow K^*\ell^+\ell^-$, we can see that in the transverse polarization, the contribution from O_7 is enhanced at low q^2 , and thus the $R_{B,M}^T$ is less sensitive to the NP in $O_{9,10}$. Measurements of the μ -to- e ratio in the transverse polarization of $B \rightarrow V\ell^+\ell^-$ at low q^2 can tell whether the NP is from the q^2 independent contribution in $C_{9,10}$ or the q^2

dependent contribution in C_7 .

- In the central q^2 region, the operators O_7 and $O_{9,10}$ will contribute destructively to the transverse polarization of $B \rightarrow V\ell^+\ell^-$. Reducing C_9 with $\delta C_9^\mu < 0$ will affect the cancellation, and as a result the decay width for the muonic decay mode will be enhanced. Thus instead of having a ratio smaller than 1, one will obtain a surplus for this ratio.
- Results for $\Lambda_b \rightarrow \Lambda$ with different polarizations are similar, but it should be pointed out that differential decay widths in Eq. (21) have neglected the kinematic lepton mass corrections. Thus the results in the low q^2 region are not accurate.
- For the $B \rightarrow K_{0,2}(1430)\ell^+\ell^-$ and $B_c \rightarrow D_s^*$, the high q^2 region has a limited kinematics, and thus the results are difficult to be measured.
- In FIG. 2, a new particle like Z' or leptoquark can contribute to the R_K and R_{K^*} . The coupling strength is unknown, and in principle it could be different from the CKM pattern. In the SM, the $B \rightarrow \pi\ell^+\ell^-$ and $B_s \rightarrow K\ell^+\ell^-$ have smaller CKM matrix elements. Thus if the NP contributions had the same magnitude as in $b \rightarrow s\ell^+\ell^-$, their impact in $B \rightarrow \pi\ell^+\ell^-$ and $B_s \rightarrow K\ell^+\ell^-$ would be much larger. This can be validated in experiments.
- The weak phases from Z' and leptoquark can be different from that in $b \rightarrow s\mu^+\mu^-$ or $b \rightarrow d\mu^+\mu^-$, which may induce direct CP violations. In the $b \rightarrow d\mu^+\mu^-$ process, the current data on $B \rightarrow \pi\mu^+\mu^-$ contains a large uncertainty [90]

$$\mathcal{A}_{CP}(B^\pm \rightarrow \pi^\pm\mu^+\mu^-) = (-0.12 \pm 0.12 \pm 0.01). \quad (26)$$

This can be certainly refined in the future. It should be noticed that the SM contribution may also contain CP violation source [91, 92] since the up-type quark loop contributions are sizable.

IV. CONCLUSIONS

Due to the small branching fractions in the SM, rare decays of heavy mesons can provide a rich laboratory to search for effects of physics beyond the SM. Up to date, quite a few quantities in B decays have exhibited moderate deviations from the SM. This happens in both tree operator and penguin operator induced processes. The so-called $R_{D(D^*)}$ anomaly gives a hint that the tau lepton might have a different interaction with the light leptons. The V_{ub} and V_{cb} puzzles refer to the difference for the CKM matrix elements extracted from the exclusive and inclusive decay modes. In the $b \rightarrow s\ell^+\ell^-$ mode, the P'_5 in $B \rightarrow K^*\ell^+\ell^-$ has received considerable attentions on both the reliable estimates of hadronic uncertainties and new physics effects. In addition, LHCb also observed a systematic deficit with respect to SM predictions for the branching ratios of several

decay modes, such as $B_s \rightarrow \phi \mu^+ \mu^-$ [93, 94]. Though the statistical significance is low, all these anomalies indicate that the NP particles could be detected in flavor physics.

In this work, we have presented an analysis of the recently observed R_K and R_{K^*} anomalies. In terms of the effective operators, we have performed a model-independent fit to the R_K and R_{K^*} data. In the analysis, we have used two sets of form factors and found the results are rather stable against these hadronic inputs. Since the statistical significance in R_K and R_{K^*} is rather low, we proposed to study a number of related rare B, B_s, B_c and Λ_b decay channels, and in particular we have pointed out that the μ -to- e ratios of decay widths with different polarizations of the final state particles, and in the $b \rightarrow d \ell^+ \ell^-$ processes are likely more sensitive to the structure of the underlying new physics. After taking into account the new physics contributions, we made theoretical predictions on lepton flavor non-universality in these processes which can stringently be examined by experiments in future.

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